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Optimum operating performance based online fault-tolerant control strategy for sensor faults in air conditioning systems

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ABSTRACT

This paper presents an online fault-tolerant control strategy. By correcting the faulty measurements with a final correcting factor, the strategy covers five steps: fault detection, construction of correcting alternatives, performance forecasting, alternatives outranking, and fault correction. System energy, indoor air quality, human thermal comfort, and control efficiency are considered as a whole to evaluate the operating performance. Taking the supply air temperature sensor faults as testing examples, the strategy is tested in a virtual air conditioning system and simulated on TRNSYS platform. The testing results show that a large fault correcting factor is obtained in the first hour, an adjusting phase presents in the next several hours, and the correction factor keeps unchanged finally. High level of calculating accuracy is required for the performance prediction model. Also, for the outranking evaluation model, the thresholds and weight coefficients should be assigned appropriately to meet the requirements of building functions and/or owners.

1. Introduction

In air conditioning systems, sensors are the indispensable components to record some physical parameters and to monitor the operating state. After long-term operation, some faults or errors may occur in sensing devices or other electronic components. These errors or biases existing in sensor outputs may increase the energy consumption, degrade the human thermal comfort, deteriorate the indoor air quality, decrease the control efficiency, and even damage some equipment. Some fault detection and diagnosis (FDD) approaches [1–5] have been designed to identify the faulty measurements and abnormal operations. Once the sensor faults are detected, an online fault-tolerant control is beneficial to keep the air conditioning system working reliably and to maintain the system performance within an acceptable range.

Several fault-tolerant control strategies have been successfully applied in some air conditioning systems. Wang and Chen [6] used a sensor recovery method to regain the measured signals and to reconfigure the control system. Once the faults generated in sensors have been diagnosed, the estimated values from an artificial neural network prediction model are input into a feedback control loop as the recovered measurements. Liu and Dexter [7] described a fault-tolerant supervisory control scheme by using fuzzy models to predict the control efficiency and by developing a computationally undemanding optimization scheme to determine the most appropriate set-points. Based on the principal component analysis, joint angle and compensatory reconstruction, Jin and Du [8] proposed a fault tolerant control method to regulate the outdoor air flow rate and to adjust the supply air temperature.

For fixed or drifting bias faults, it is easy to reconstruct the faulty measurements and to realize fault-tolerant control if FDD approaches can diagnose the fault size. For the highly nonlinear systems such as heating, ventilation and air-conditioning systems, however, it is very difficult to identify the fault severity, for example, when the measurements are under noise or uncertain disturbance conditions. In this case, one problem is to develop a fault-tolerant control strategy without identifying the fault severity.

On the other hand, how to evaluate the operating performance of air conditioning systems is an urgent problem. When the thermal comfort and indoor air quality are sustained in a typical air conditioning system, different operating conditions will result in various system energy consumption [9,10]. Certainly, human comfort, indoor air quality, energy consumption and other performance indices should be balanced to realize the optimum operation.

Another problem is that sensor faults may affect the control efficiency of some controllers. If the sensor measurements with positive or negative faults are input into a controller, the resulting response will moderate the actuator excessively or insufficiently. Once the actuator is adjusted up to the maximum position, the increasing response from the controller will not be executed. In other words, the actuator may keep at the maximum position and the controller will lose the controlling function. Similarly, decreasing response will not be executed if the actuator is up to the minimum position. As a result, the control efficiency should be taken into account during the evaluation of operating performances.

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To solve these problems, this study proposes an online fault-tolerant control strategy by optimizing the system operating performance. Fractal correlation dimension (FCD) algorithm is used to detect whether some faults have occurred or not. The support vector regression (SVR) process models are employed to provide the references of sensor measurements. After the faults have been detected, the correcting alternatives are constructed by the predicted references with given intervals and steps. Then, each alternative is input into the SVR performance prediction models to predict their respective operating parameters. Elimination and choice translating reality (ELECTRE) algorithm is used to develop a performance evaluation model, and the optimum operating state can be achieved by outranking all the different alternatives. The final fault correcting factor is calculated by all previous correcting factors.

2. Outline of fault-tolerant control strategy

Fig. 1 illustrates the flowchart of the online fault-tolerant control strategy for air conditioning systems. The fault signals will be corrected in the next hour. Namely, the correcting factor of measured values in the current hour is derived from the correcting factor of predicted values in the previous hour. The detailed functions are formulated in Section 2.5. The corrected values and other parameters are input into the SVR performance prediction model. All correcting alternatives are outranked by the ELECTRE evaluation model. The correcting factor of the optimum operating alternative is selected to correct the faulty sensor measurements in the next hour. The final fault correcting factor is the product of all correcting factors.

The proposed strategy covers five steps.

Step 1 Fault detection. The FCD strategy is used to detect small bias faults, and the statistical residuals method is employed to detect high bias faults. A SVR process prediction model is used to provide the references.

Step 2 Construction of correcting alternatives. If the generated fault has been detected, dozens of correcting alternatives are constructed by the specified interval and step. Each correcting alternative follows by an operating state.

Step 3 Performance forecasting. This scheme predicts the operating performance of each alternative.

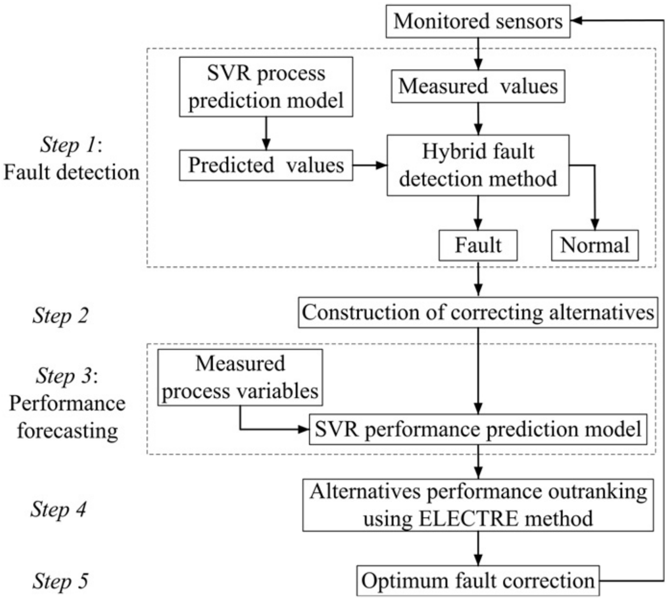

Fig. 1. Flowchart of online fault-tolerant control strategy for air conditioning systems.

Step 4 Alternatives outranking. An ELECTRE performance evaluation model is developed to outrank all correcting alternatives.

Step 5 Fault correction. This scheme calculates the final fault correcting factor to correct the faulty measurements.

2.1. Fault detection

The statistical residuals between measured and predicted data are compared with the specified thresholds to identify whether the large bias faults have generated or not [11,12]. This classical fault detection method, however, is difficult to detect small bias fault especially under noisy conditions. Using a correlation dimension to depict structural characteristics from irregular signals, the FCD-based method can be effectively applied to detect the small bias fault [2]. Different from the direct residual-based method, the FCD-based method can extract the dimension value of feature vector to represent the curve variation. It is so sensitive to tiny variation that it can identify the relative small bias. Further, the number of deviations to detect fault is significantly reduced due to only one dimension value to represent the curve variation.

As the reference to compare with measured signals, the predicted value can be obtained from several methods including quantitative and qualitative priori knowledge based methods, and data driven models (namely gray box model and black box model) [13]. Different from the artificial neural networks followed a heuristic path with applications and extensive experimentation preceding theory, the support vector machine (SVM) involves sound theory first, then implementation and experiments [3]. The SVM for regression, namely SVR, which often outperforms artificial neural networks with less over-fitting, uses statistical learning theory to solve the regression problems by introducing an alternative loss function. In the study, the ν–SVR algorithm [14] is employed to provide the reference for fault detection and to forecast the operating performance under different operating conditions (see Section 2.3).

2.2. Construction of correcting alternatives

If the fault is detected, it is urgent to evaluate its severity and make an appropriate correction. The ideal correction may bring the faulty system operation into the optimum operating state. To approach this optimum correction, this study constructs dozens of correcting alternatives and tries to select the optimum one. As discussed in Section 2.1, the approximate value of faulty sensor outputs can be achieved from the SVR prediction model. The calculation from the well-trained prediction model is defined as the predicted value. Adjusted by the specified interval and step, dozens of values can be obtained.

The relationship between the actual value and the measured value is described as

$$a_{meas} = a_{act} \times \left(1 + \Delta a_{pct}\right) \tag{1}$$

where a_{meas} is the measured value, a_{act} is the actual value, and Δa_{pct} is the deviating percentage between them.

The value from some prediction models is considered as the approximate of the actual, namely $a_{act} \approx a_{pred}$, and thus

$$a_{meas} \approx a_{pred} \times \left(1 + \Delta a_{pct}\right) \tag{2}$$

where a_{pred} means the predicted value.

A set of correcting alternatives are constructed by the predicted value with the specified interval and step. Assuming that the correcting interval is $[-\delta, +\delta]$ and the correcting step size is Δs, the correcting